Power Beaming for Deep Space and Permanently Shadowed Regions

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***Abstract**: Power beaming involves the wireless transfer of power, and could provide a revolutionary new way to power spacecraft and vehicles operating in difficult to access regions. Power beaming has the potential to represent an alternative solution to power spacecraft and landers where sunlight is unavailable. It could provide a source of power to robotic systems in permanently shadowed regions or power landers and rovers from orbiting spacecraft (e.g.,Moon, Mars, Europa, Enceladeus, Miranda).*

1. Introduction

Future exploration of the solar system and beyond is focused on visiting challenging environments with new mission concepts, all of which are limited by the available power. New concepts include the use of smaller robotic systems (such as Moondiver and Cooperative Autonomous Distributed Robotic Explorers or CADRE), which have been proposed for exploration in difficult to access regions of planetary surfaces such as shadowed cliffs, caverns, lava tubes, or permanently shadowed craters. New mobility concepts are under development, for imaging and sampling these regions, on the Moon, Mars, small bodies and the ocean worlds of the solar system. One approach is to enable existing spacecraft power systems to support other spacecraft and probes via power beaming. Power beaming involves the wireless transfer of power [1, 2], and could provide a revolutionary new way to power spacecraft and vehicles operating in difficult to access regions where sunlight is unavailable. It could provide a source of power to landers and rovers from orbiting spacecraft (e.g. the Moon as shown in Fig. 1a, Mars, Europa, Enceladeus, Miranda). To achieve high power beaming, the orbiter could use a large lightweight solar array structure [3] combined with ultralight solar cells made for example of perovskite [4]. Another application is to beam power from a central node lander to CADREs located in permanently shadowed regions (PSR) such as shadowed cliffs, caverns, lava tubes, or craters. The Moon's Shackleton crater is a prime example of this kind of location. Fig. 2b shows a solar powered lander that is beaming power to a CADRE operating in the permanently shadowed Shakleton crater. However, laser power beaming technology and systems are at a low TRL, and many technical challenges need to be resolved before it can be baselined for future missions. In the recent years, there has been growing interest in power beaming and this could become a mission enabler. There is a need to develop efficient end-to-end power systems (from the transmitter to the receiver), as well as new mission concepts and architectures that would take full advantage of these new capabilities.

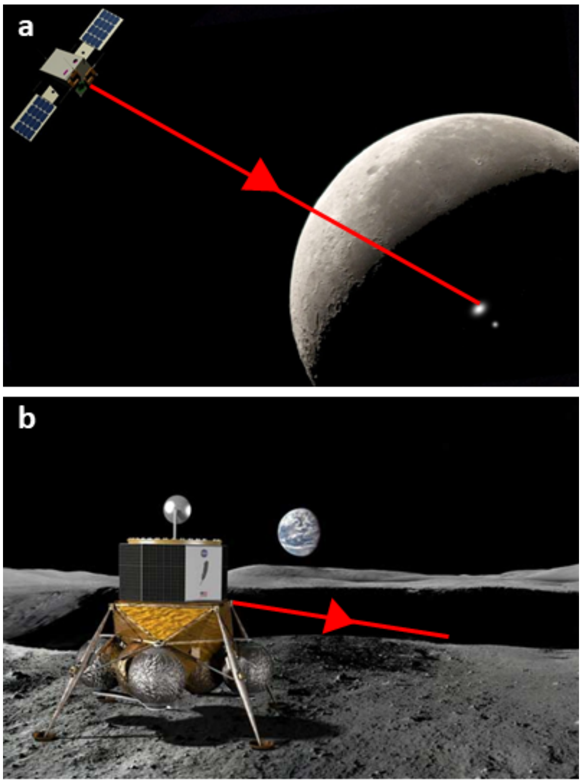

Figure 1. a) Orbiting solar-powered vehicle provides power to landed assets during lunar night. b) Power beaming to a CADRE in the permanently shadowed Shakleton crater. Artist's concept of Blue Origin's Blue Moon lunar lander. Credit: Blue Origin. The red line shows the power beaming direction.

2. Comparison with Solar Photovoltaics

We evaluate the benefits of power beaming compared to solar photovoltaics. In the case of PSRs, power beaming enables missions that wouldn't be possible using solar photovoltaics due to the absence of sunlight. Assuming perfect pointing of a 1 kW laser beam at 1064 nm and a 65% efficient tuned laser power converter (LPC) receiver array, power beaming would provide 650 W to a CADRE located in a PSR. A tether could also be used in PSRs but it would limit mobility. Moreover, a tether suffers from I^2R losses as opposed to a laser beam. In the case of providing continuous power throughout the lunar night, solar photovoltaics would only operate during the day and require 336 hours of energy storage for the night. Power beaming from a solar powered orbiter as shown in Fig 1a and located at the Earth-Moon Lagrangian point would significantly reduce the need for energy storage technologies such as batteries or regenerative fuel cells.

Short wavelength and high power lasers in the visible and near infrared coupled with high efficiency LPCs derived from the fast growing photovoltaic industry represent a game changing opportunity for efficient power beaming. The beam size from a laser is limited by diffractive optics and the spot size is about:

$$d \approx \frac{2.44\lambda L}{D}$$

where L is the distance over which the power is beamed, λ is the laser wavelength, and D is the diameter of the laser aperture. Using a 1064 nm laser with a 10 kW optical power output at a distance of 60,000 km, which is approximately the Earth-Moon L1 distance, a 1 m diameter aperture laser could transmit 6.5 kW electrical power through a 156 m diameter LPC target without any losses due to the beam divergence.

3. Power Beaming Experiment

We used GaAs (1.424 eV, 870 nm) and InGaAs (1.1 eV, 1130 nm) LPCs from Spectrolab designed for direct laser illumination. At the Jet Propulsion Laboratory (JPL), we tested and evaluated the performance of these Spectrolab LPCs using an 808 nm laser in the JPL variable-temperature test chamber. The devices were measured at

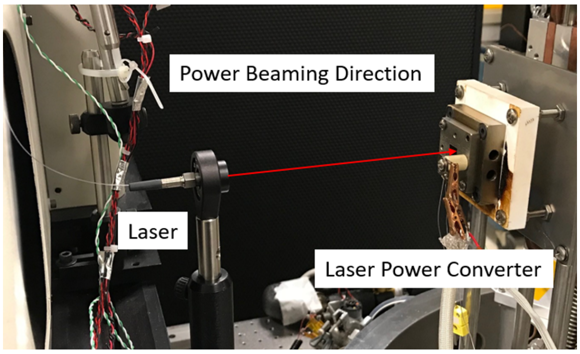

Figure 2. Power beaming setup at JPL.

high temperatures (up to 200°C) to simulate heating associated with high power transmission. Current-voltage (*I-V*) and external quantum efficiency (*EQE*) measurements were done to characterize the devices. JPL collaborated with Spectrolab to improve the LPC design and to further mature this technology in order to reduce series resistance associated with high received power and increase the power converter operating efficiency within the required operational temperature and frequency conditions. Figure 2 is a photograph of the power beaming test setup that was developed at JPL. It shows an 808 nm high power laser beam coming out of an optical fiber. The laser was from the company Boston Laser and it was powered using a Spectra Diode Labs SDL 820 laser diode driver. To determine the optical output power of the laser, we used an optical power meter placed in front of the optical fiber prior to the experiment. For the actual power beaming experiment, the laser beam was collimated using an optical lens and directed towards a LPC about 20 cm away from the optical lens. Figure 3 presents *I-V*

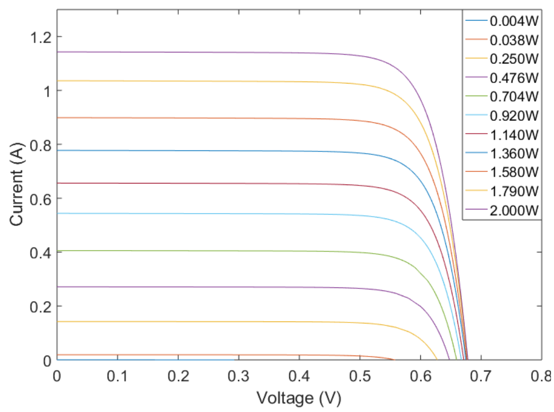

Figure 3. Current-Voltage measurement of the LPC while illuminated by an 808 nm wavelength laser beam.

measurements of an InGaAs LPC while illuminated by the 808 nm laser. Power was increased up to 2 W and the converted power density increased linearly with the beamed power. At 2 W power, the converted electrical power density was about 12 kW/m2. This corresponds to about 30 times a regular solar array power output at 1 AU.

4. Conclusion

Power beaming represents a game changing opportunity for deep space exploration. In this paper, we described potential space mission scenarios that could benefit from power beaming. Measurements carried at JPL show promising results for laser power transmission in the near infrared where beam divergence is limited.

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References

[1] P. Sprangle, B. Hafizi, A. Ting, and R. Fischer, "High-power lasers for directed-energy applications," *Applied Optics,* vol. 54, pp. F201-F209, 2015/11/01 2015.

[2] K. Jin and W. Zhou, "Wireless Laser Power Transmission: A Review of Recent Progress," *IEEE Transactions on Power Electronics,* vol. 34, pp. 3842-3859, 2019.

[3] E. Gdoutos, C. Leclerc, F. Royer, D. A. Türk, and S. Pellegrino, "Ultralight Spacecraft Structure Prototype," in *AIAA Scitech 2019 Forum*, ed.

[4] M. Kaltenbrunner, G. Adam, E. D. Głowacki, M. Drack, R. Schwödiauer, L. Leonat, *et al.*, "Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air," *Nature Materials,* vol. 14, p. 1032, 08/24/online 2015.